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Impacts of climate change and human activities on the flow regime of the dammed Lancang River in Southwest China

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ABSTRACT

The Lancang River (LR) in China (the upper portion of the Mekong River which is among the world's most important transboundary rivers) originates on the Tibetan Plateau and provides important freshwater resources for living, agriculture, industry, and hydropower generation for millions of people downstream. The natural flow regime of the LR is critical to sustain native biodiversity and ecosystem integrity; however, it has been changing due to the combined effect of climate change and human activities. Accurate quantification of the impacts of climate change and human activities on changes in the flow regime is a prerequisite for water resources and hydropower exploitation and environmental protection. This study aims to evaluate climate- and human-induced impacts on the LR during 1980–2014. A distributed hydrological model CREST-snow combined with remote sensing and streamflow data and the Budyko framework were jointly used to address this scientific question during three time windows determined by the Mann–Kendall test and the history of dam construction. Results show that compared with the baseline period (1980–1986) when no dam was constructed, significant changes ($\sim -6\%$) in mean annual streamflow occurred during 1987–2014, particularly after 2008 when the construction of the largest hydropower plant (Nuozhadu) in the Mekong River basin began. Climatic change contributed ~57% to streamflow changes during the transition period (1987–2007), whereas human activities contributed ~95% during the post-impact period (2008–2014). At the seasonal scale, climatic variation plays a more significant role during the dry season (December–May), with precipitation the most important factor among climate variables, whereas human activities contributed more during the wet season (June–November), benefiting the downstream areas through mitigating floods. Among human activities, reservoir construction is a dominant factor affecting streamflow over agricultural, industrial, and domestic water uses. The findings of this study enhance our understanding of hydrological changes in the LR basin that may impact the Lower Mekong River, serve as a basis for water resources and hydropower exploitation and environmental protection, and highlight the need for considering reservoir operation strategies in streamflow projections in similar basins globally under climate change scenarios.

1. Introduction

As the most important transboundary river in the world, the Mekong River (MR) flows through six countries (i.e., China, Myanmar, Laos, Thailand, Cambodia, and Vietnam) with a total length of ~4,350 km and a drainage area of ~795,000 km^2 (MRC, 2010). The Lancang River (LR) in China, i.e., the upper portion of the MR, originates on the Tibetan Plateau (TP) and flows through Qinghai, Tibet, and Yunnan Provinces. The LR provides important freshwater resources for domestic, agricultural, industrial uses, and hydropower to China and downstream countries. The natural flow regime of the LR is critical to native biodiversity and ecosystem integrity in rivers (Poff et al., 1997). In addition, an improved understanding of the hydrology of the basin is the scientific foundation on integrated water resources management (Carlisle et al., 2010; Commission, 2009) and on modeling potential changes in the streamflow of the LR in the future.

Both climate change and human activities have exerted significant pressure on the LR. First, runoff from the TP tends to be sensitive to climate change as a result of changing precipitation and snow and glacier melting processes due to climate warming (Chen et al., 2017; Chen et al., 2018; Huang et al., 2018a; Lauri et al., 2012; Long et al., 2014; Lutz et al., 2014; Tang et al., 2018). Second, growing population leads to increased water resource and energy demands that may subsequently result in extensive hydropower exploitation in both the

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mainstream and tributaries of the LR (Pokhrel et al., 2018). Quantifying the impacts of climate change and human activities on the streamflow of the LR is therefore fundamental to water resource management and environmental protection and therefore has received considerable attention from the scientific community (Immerzeel et al., 2009; Jeelani et al., 2012; Räsänen et al., 2017).

Recent studies associated with the impact of hydropower generation mainly focused on historical changes in streamflow of the lower MR (Cochrane et al., 2014; Lu et al., 2014; Mohammed et al., 2018; Räsänen et al., 2012; Räsänen et al., 2017). Lu et al. (2014) and Räsänen et al. (2017) examined changes in river discharge at the Chiang Saen gauging station in Northern Thailand since 1960, whereas Li et al. (2017a) used streamflow observations at five gauging stations along the mainstream of the MR to assess the alteration of flow regimes over the period of 1960–2014. These studies mostly compared the streamflow before and after dam construction based on streamflow observations and confirmed the significant effect of cascade reservoirs upstream.

However, discrepancies of the findings exist due to different study periods and changes in the intra-annual streamflow distribution. Lu et al. (2014) found a 9% decrease in discharge at the Chiang Saen gauging station in August but a 15% increase in discharge in July over the post-dam period (1992–2010) than that over the pre-dam period (1960–1991). But Räsänen et al. (2017) found an increase of 121–187% in discharge during Mar–May and a decrease of 32–46% in discharge during July–August in 2014 compared with the mean discharge over the period 1960–1990 at the Chiang Saen gauging station. Mohammed et al. (2018) explored the variability in streamflow of the Lower MR by examining changes in the Upper MR inflow using a hydrological model. Moreover, several studies simulated the effects of projected climate change scenarios and reservoir operation strategies on streamflow. For example, Ngo et al. (2016) applied the Soil Water Assessment Tool (SWAT) and Water Evaluation and Planning (WEAP) models to the tributaries of the Lower MR in Vietnam and Cambodia for the future period 2010–2100 to assess the impacts of different reservoir operation strategies on flow regimes. Wang et al. (2017) adopted the Geomorphology-Based Hydrological Model (GBHM) to study the combined effect on floods in the MR basin from 2010 to 2099, indicating that reservoir operation could mitigate the effect of flood intensification caused by climate change before 2060.

Despite recent efforts, the impacts of climate change and human activities on the streamflow of the LR have remained inadequately assessed. First, few studies quantified climate and human impacts on the historical streamflow of the LR. Tang et al. (2014) used a Back-Propagation Artificial Neural Network (BP-ANN) model and concluded that human activities exerted a larger impact on streamflow changes in the LR than climatic variations (54.6% and 45.4%, respectively) during 1986–2008. Second, as mentioned above, the LR has been less studied than the MR or only studied over a short time period (Tang et al., 2014; Zhao et al., 2012). The LR originates at elevations of over 5100 m on the TP, with its runoff sensitive to climate change as a result of snow and glacier melting (Immerzeel et al., 2009; Lutz et al., 2014). Assessing the hydrological impacts of climate change over the LR basin thus requires more sophisticated hydrological models with a snow and glacier module and adopts a multiple dataset calibration method to ensure both accurate simulation of streamflow and a reasonable contribution of snow and glacier meltwater to total runoff (Finger et al., 2015).

The overall objective of this study was therefore to quantify climate- and human-induced impacts on changes in streamflow of the LR during the period 1980–2014. To achieve this objective, we relied on the Coupled Routing and Excess STorage (CREST) model (Wang et al., 2011) coupled with a snow and glacier melting module (Chen et al., 2017) (termed CREST-snow hereafter) and streamflow observations at the Yunjinghong gauging station at the outlet of the LR basin to generate historical natural streamflow. We analyzed interannual, seasonal, and monthly changes in streamflow and quantified the contributions

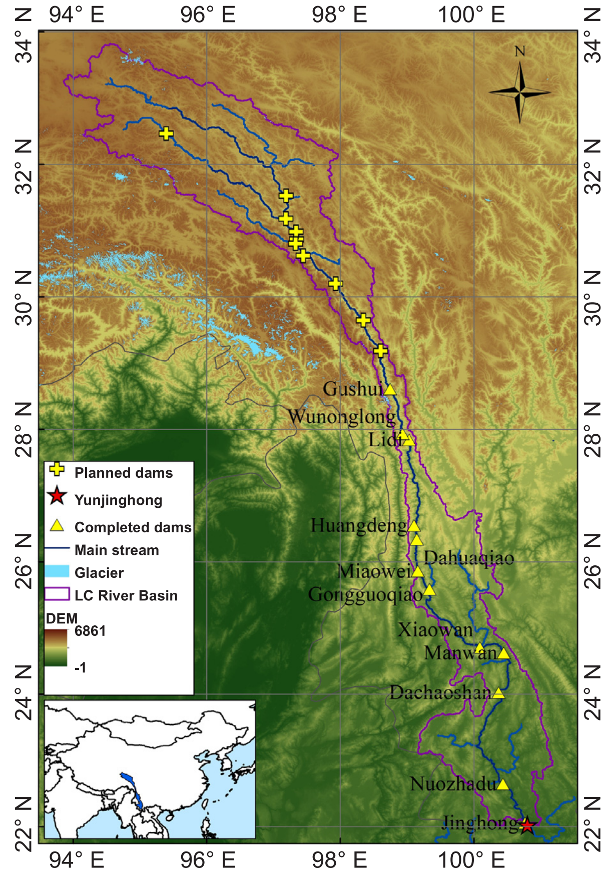

Fig. 1. Location of the LR basin, Yunjinghong streamflow gauging station, dams including those to be built shown by yellow crosses, mainstream, and elevations (m). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

from climatic and anthropogenic effects. In addition, we partitioned the impacts of human activities during 1980–2010 based on a global monthly gridded (0.5°) sectoral water withdrawal dataset (Huang et al., 2018b). The findings advance our understanding of hydrological changes in the LR basin and highlight the role of reservoir construction and operation in influencing streamflow regimes. This study can serve as a basis for examining climate and human impacts on streamflow for dammed rivers, and provide reference for projecting future streamflow changes, particularly for snow-fed rivers that are dictated by reservoir operation.

2. Study area

The LR is located within the domain 22°05′–33°40′N and 93°50′–101°30′E in Southwest China (Fig. 1), with a total length of ~2,140 km and a drainage area of ~142,000 km^2 (Long et al., 2014). It has a complex terrain, with a mean elevation of ~3,300 m and an elevation difference of ~5,500 m decreasing from the northwest to the southeast.

The LR features a humid climate with a mean annual precipitation of ~735 mm based on a 35-year record (1980–2014) of the China Gauge-based Daily Precipitation Analysis (CGDPA) product (Shen and Xiong, 2016). The westerlies and Indian monsoon bring abundant moisture and rainfall over the LR basin from June to September, which accounts for nearly 70% of the annual rainfall. Correspondingly, streamflow in the LR also exhibits strong seasonality, with 70% of the annual discharge and the peak discharge normally occurring between August and September (Jacobs, 2002).

The unique geographical features and the large energy demand in

Table 1
Detailed information on six largest dams along the Lancang River mainstream.

Hydropower station	Manwan	Dachaoshan	Jinghong	Xiaowan	Gongguoqiao	Nuozhadu
Date of river closure	1987.12	1997.11	2005.1	2004.10	2008.12	2007.11
Date of power generation	1993.6	2003.1	2008.6	2009.9	2011.11	2012.9
Drainage area (10^4 km^2)	11.45	12.10	14.91	11.33	9.73	14.47
Mean annual discharge (m^3/s)	1230	1340	1840	1220	985	1750
Dead reservoir storage (10^8 m^3)	6.68	3.71	8.10	43.50	3.16	103.00
Total reservoir storage (10^8 m^3)	9.20	9.40	14.00	153.00	3.65	227.00
Installed capacity (10^4 kW)	150	135	150	420	90	500
Height (m)	132	115	118	300	105	255

Yunnan Province and Eastern China have contributed to the burgeoning development of hydropower plants in the LR basin (Chen et al., 2010; Hennig et al., 2013). The six largest dams (storage capacity > 1 hundred million m^3) on the mainstream were included in our analysis, with their detailed information listed in Table 1.

3. Data and methods

3.1. Data

Streamflow observations at the Yunjinghong gauging station for the time period 1980–2014 were obtained from the China Hydrology Data Project (http://depts.washington.edu/shuiwen/) (Henck et al., 2011) and local water resources administrations. Snow water equivalent (SWE) was estimated based on a snow depth product from the Environmental and Ecological Science Data Center for West China (http://westdc.westgis.ac.cn/) (Che et al., 2008; Dai et al., 2015, 2012) and snow density calculated using in situ measured snow depth and snow pressure (Chen et al., 2017). Here the discharge and SWE dataset were jointly used to calibrate CREST-snow and partial discharge data were used to validate the hydrological model.

The CGDPA precipitation product developed by the National Meteorological Information Center of the China Meteorological Administration, was generated using rainfall measurements of ~2400 national gauges and the climatological optimal interpolation (OI) algorithm (Shen and Xiong, 2016) (http://cdc.nmic.cn). Other meteorological data, including daily time series of maximum, mean, and minimum air temperatures, dew point temperature and pressure, were obtained from the ERA-Interim product, the latest global atmospheric reanalysis produced by European Centre for Medium-Range Weather Forecasts (ECMWF). Both CGDPA and ERA meteorological data were converted from a resolution of 0.25° to a resolution of 0.0625° using the nearest neighbor method for driving the hydrological model.

Daily temperature, dew point temperature, and pressure estimates for the period 1980–2014 were used to calculate wet-bulb temperature and force CREST-snow. ERA-interim temperature estimates were used to estimate potential evapotranspiration according to the Hargreaves method (Hargreaves and Samani, 1985), with the parameters adjusted to be applicable to Southwest China (Hu et al., 2011). The digital elevation model (DEM) provided by NASA's Shuttle Radar Topography Mission (SRTM) at a spatial resolution of 0.0083°, was used to delineate the LR basin boundary and derive flow direction and flow accumulation for use in CREST-snow.

Huang et al. (2018b) generated a global monthly gridded (0.5°) sectoral water withdrawal dataset for the period 1971–2010, using various sources of reported data and some spatial and temporal statistical downscaling algorithms. This dataset comprises six water use sectors including irrigation, living, electricity generation (cooling of thermal power plants), livestock, mining, and manufacturing and was used here to partition the effects of human activities on streamflow.

3.2. Methodology

3.2.1. CREST-snow hydrologic model

The Coupled Routing and Excess STorage (CREST) model (Wang et al., 2011) is a distributed hydrological model jointly developed by the University of Oklahoma and the National Aeronautics and Space Administration (NASA) SERVIR Project Team (http://www.servir.net). The CREST model computes infiltration and runoff using the variable infiltration capacity curve updated from the Xinanjiang model (Zhao, 1992) and VIC model (Liang et al., 1996), and simulates sub-grid cell routing in a study basin employing linear reservoirs, which results in more accurate streamflow simulations than that using old routing methods (Shen et al., 2016; Wang et al., 2011).

CREST has been coupled with a snow and glacier melting module based on the temperature-index method (Chen et al., 2017), in which wet-bulb temperature was used in this study to partition total precipitation into solid and liquid phases because precipitating droplets (e.g., rain, sleet, and snow) have a temperature closer to wet-bulb temperature than air temperature (Ding et al., 2014). CREST-snow was set up at a spatial resolution of 0.0625° (~7 km at the equator) to simulate daily streamflow at the Yungjinghong gauging station on the LR.

The performance of the model was evaluated using the Nash-Sutcliffe model efficiency coefficient (*NSE*) (Nash and Sutcliffe, 1970), the Nash-Sutcliffe Efficiency Coefficient with logarithmic values (*LogNSE*), correlation coefficient (*R*), and relative differences (*Bias*). *NSE* has been widely used to measure the overall performance of the hydrological model whereas *LogNSE* could better assess the simulation of low flows (De Vos and Rientjes, 2008). *Bias* is defined as the sum of the difference between simulated and observed runoff, divided by the sum of observed runoff.

3.2.2. Identification of streamflow break points

The Mann–Kendall test (Hamed and Rao, 1998) was used to identify the break point of streamflow time series at the Yunjinghong gauging station for the period 1980–2014. The intersection point approaches year 2008, corresponding to the year when the construction of the largest reservoir, Nuozhadu, on the LR started and the river was intercepted. The first reservoir on the LR, Manwan, was under construction since 1987.

Based on the history of dam construction and trends in streamflow, we divided the historical 35-year period (1980–2014) into three time windows: (1) the baseline period 1980–1986 when no dam was constructed, (2) the transition period 1987–2007 when small dams were constructed but there was no significant change in the trend of streamflow, and (3) the post-impact period 2008–2014 when large dams were constructed and significant changes on streamflow were observed. Daily streamflow observations during the baseline period were used to calibrate the model, whereas streamflow observations during the transition period were used to validate the model, because the streamflow did not significantly change during the transition period.

Table 2
Performance metrics of simulated discharge at the Yunjinghong gauging station on the LR for the calibration, validation, and overall periods, respectively.

Time period	*NSE*	*LogNSE*	*R*	*Bias*
Calibration (1980–1986)	0.73	0.80	0.91	0.10
Validation (1987–2007)	0.53	0.70	0.82	0.12
Overall	0.57	0.73	0.85	0.12

3.2.3. Contribution of climate change and human activities

Both climate change and human activities can alter the flow regime of the LR. In this study, CREST-snow and a method based on the Budyko hypothesis were used to evaluate these impacts. The total change in observed streamflow (ΔQ) can be attributed to the combined impacts of climate change (ΔQ_{cc}) and human activities (ΔQ_{ha}):

$$\Delta Q = \Delta Q_{cc} + \Delta Q_{ha} = O_i - O_0 \tag{1}$$

where O_i and O_0 are the observed mean annual streamflow (m^3/s) for the assessment period (transition or post-impact period) and the baseline period, respectively.

Streamflow simulation using CREST-snow represents the impacts of variability in precipitation and temperature that reflects a changing climate system on the flow regime. CREST-snow was used to generate natural streamflow in response to climate change and variability. The climate-induced change in streamflow can be calculated as follows:

$$\Delta Q_{cc} = R_i - R_0 \tag{2}$$

where R_i is the simulated annual streamflow for the assessment period (m^3/s) and R_0 is the simulated annual streamflow for the baseline period (m^3/s). Thus, the human-induced streamflow change can be calculated as the difference between$\Delta Q$and ΔQ_{cc}:

$$\Delta Q_{\rm ha} = \Delta Q - \Delta Q_{\rm cc} \tag{3}$$

We defined $I_{\rm cc}$ and $I_{\rm ha}$ as the contributions of climate change and human activities to the total streamflow change:

$$I_{\rm cc} = \frac{|\Delta Q_{\rm cc}|}{|\Delta Q_{\rm cc}| + |\Delta Q_{\rm ha}|} \times 100\%, \quad I_{\rm ha} = \frac{|\Delta Q_{\rm ha}|}{|\Delta Q_{\rm cc}| + |\Delta Q_{\rm ha}|} \times 100\% \tag{4}$$

Eqs. (1)–(4) are also appropriate for seasonal analysis of contributions of climate change and human activities during wet season (June–November) and dry season (December–May) or monthly analysis.

The Budyko framework has been widely used to separate the effects of climate change and human activities on streamflow changes (Guo et al., 2015; Li et al., 2011; Li et al., 2017a). In this study, we decomposed the climate and human impacts based on the Budyko hypothesis at the annual timescale to make a cross-validation with our estimates from CREST-snow. We adopted the Ture-Pike equation (Pike, 1964) and quantified the climate-induced change ($\Delta Q'_{\rm cc}$) of streamflow:

$$E/P = (1 + \varnothing^{-2})^{-0.5} \tag{5}$$

$$\varnothing = E_0/P \tag{6}$$

$$\Delta Q'_{\rm cc} = \frac{\partial Q}{\partial P}\Delta P + \frac{\partial Q}{\partial E_0}\Delta E_0 \tag{7}$$

where the climate dryness index ($\varnothing$) is the ratio of the mean annual potential evapotranspiration (E_0) to the mean annual precipitation (P). For the long-term annual water balance, soil-water storage change is assumed to be negligible, and the actual mean annual evapotranspiration (E) can be expressed as $E = P - Q$ in Eq. (5).

3.2.4. Partitioning effects of water use

Five water use sectors including irrigation, living, livestock, mining, and manufacturing of the global monthly gridded (0.5°) sectoral water withdrawal dataset (Unit: mm) and dead reservoir capacity data listed in Table 1 were used to partition the effects of human activities on the flow regime of the LR for the period 1980–2010. Annual water use was calculated by spatially averaging water use values across all grid cells within the LR basin and then summing monthly values to obtain annual average values. Streamflow variation caused by each type of water use sectors was calculated using the mean annual water use value during the period 1987–2010 minus that during the baseline period 1980–1986.

Dead reservoir storage is referred to as water in a reservoir that cannot be drained by gravity through a dam's outlet works, spillway or power plant intake. We summed the dead reservoir storages of the completed reservoirs during 1987–2010 (Table 1) and converted the volumetric values into millimeters based on the drainage area of the LR basin, for the convenience of comparison. The total dead reservoir storage was used to characterize the streamflow change caused by reservoir construction.

4. Results

4.1. CREST-snow model simulations

Table 2 shows monthly performance metrics of the simulation with CREST-snow. For the calibration period, the *NSE* and *Bias* values were found to be 0.73 and 0.1 respectively. For the validation period, the *NSE* and *Bias* values were 0.53 and 0.12. Some overestimates of streamflow were found particularly for the high peaks of 1992, 1994 and 2006, as seen from Fig. 2, and we postulated that it might result from the overestimated precipitation estimates used in this study. Previous studies suggested that hydrological modeling with $NSE >$ 0.50 can be considered satisfactory (Moriasi et al., 2007). Here, CREST-snow for the overall period 1980–2007 showed satisfactory performance in terms of both *NSE* (0.57) and *R* (0.85). The calibrated

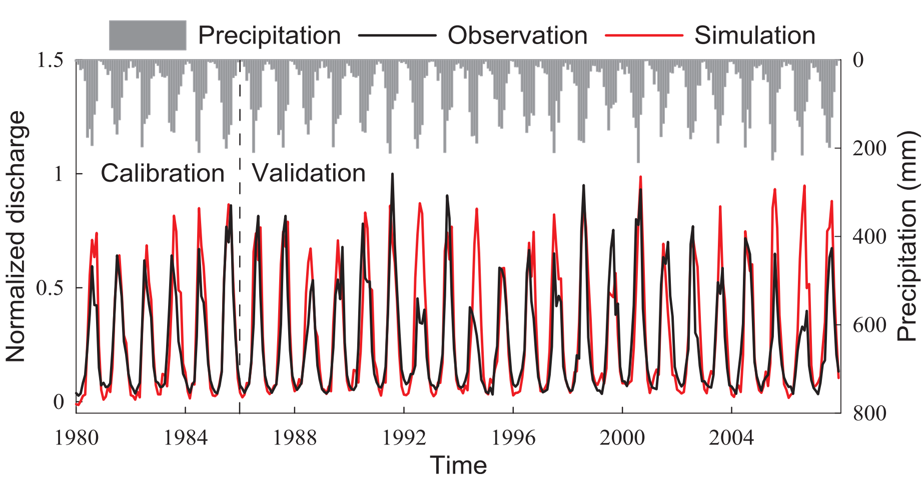

Fig. 2. Normalized monthly simulated and observed discharge at the Yunjinghong gauging station and corresponding monthly precipitation for the LR basin for the calibration (1980–1986) and validation (1987–2007) periods, respectively. The discharge was normalized as the difference between the discharge and the minimum discharge divided by the difference between the maximum and minimum discharge at the Yunjinghong gauging station during 1980–2007.

parameters were therefore considered suited to simulate natural streamflow.

Note that low flows were simulated better than peak flows during the overall period, with a higher *LogNSE* value (0.73) than *NSE* (0.57). This is largely due to the impact of precipitation input. We used meteorological data including precipitation, potential evapotranspiration, air temperature and wet-bulb temperature for the later decades as input to simulate the historical natural streamflow for the transition period 1987–2007 and the post-impact period 2008–2014. The results and analyses are presented in the following section.

4.2. Trend analysis of hydrological variables during 1980–2014

During 1980–2014, the proportional contribution of snowmelt to total basin discharge was relatively low (~2%) in the LR basin. The impact of glacier meltwater on runoff was even lower (~0.2%) due to the very limited glacier coverage within the study basin (Fig. 1). The simulation results therefore suggest that rainfall is the dominant factor affecting runoff in the LR basin because of the relatively low contributions of snow and glacier meltwater to total runoff. Time series of annual mean precipitation, observed streamflow, and simulated natural streamflow from 1980 to 2014 were shown in Fig. 3. Both precipitation and simulated natural streamflow increased at a rate of 0.98 mm/yr^2 (not significant) and the simulated natural streamflow increased at a rate of 0.70 mm/yr^2 (not significant). Natural runoff was simulated using the parameters calibrated for the baseline period and was assumed to have been influenced only by climate change, which was also demonstrated by the high R value (0.91) between precipitation and the simulated natural streamflow.

Note that during the period 1980–2014, mean annual temperature of the LR basin was rising at a rate of 0.023 °C/yr ($p < 0.01$), and snow and glacier meltwater increased at a rate of 0.064 mm/yr^2 ($p < 0.05$). However, the observed streamflow exhibited a decreasing trend at a rate of 2.96 mm/yr^2 ($p < 0.1$), due to the combined effect of both climate change and human activities. As seen from Fig. 3, the discrepancies between the observed streamflow and natural streamflow enlarged since 1987 due to reservoir construction, demonstrating the nonnegligible impact of human activities on the flow regime of the LR.

At the seasonal scale, the observed and simulated streamflow also showed considerable changes during the transition and post-impact periods compared with the historical streamflow during the baseline period. Dashed lines in Fig. 4 show the observed streamflow at the Yunjinghong gauging station for all three periods. The dry season streamflow (December–May) was lowest in the baseline period. During the transition period, the dry season streamflow showed a slight increase, whereas the wet season streamflow (June–November) showed little changes. During the post-impact period, streamflow in both dry and wet seasons showed significant changes (~20% and ~40%) compared with that during the baseline period, which may be caused by reservoir construction and filling.

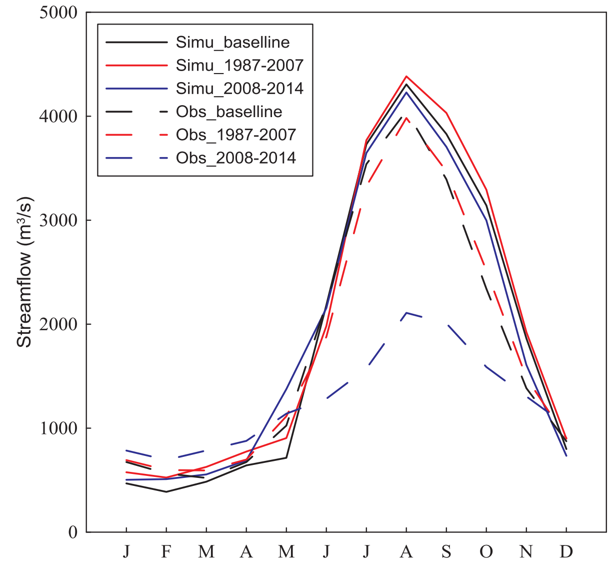

Fig. 4. Time series of observed streamflow (dashed lines) and simulated natural streamflow (solid lines) at the Yunjinghong gauging station for the baseline, transition and post-impact periods, respectively.

Monthly simulated natural streamflow at the Yunjinghong gauging station over the three periods is shown in Fig. 4 using solid lines. The natural streamflow changed little in the wet season during the three periods. In addition, the observed streamflow deviated considerably from the simulated natural streamflow (i.e. with large reservoir construction) during the period 2008–2014. Before year 2008, the difference between the observed and simulated natural discharge was apparently smaller. At the monthly scale, the observed streamflow showed a decrease of 40% – 56% in June–September but an increase of 11% – 50% in March–May on the mean discharge over the post-impact period than that over the baseline period. However, the dam construction did not affect the timing of the peak flow that was still in August. Also, the trend in low flows did not change, with the February–March low discharge period preceded by high discharge in January and followed by a sudden decline in March.

Fig. 5 shows time series of observed streamflow during the baseline period and during the first year after each of the six hydropower plants (Table 1) was put into operation. The reservoir operation in the wet season became increasingly significant with more reservoirs built over time except 1994, because there was a severe drought in the LR basin around 1994 (Xu, 2018). The inset in Fig. 5 shows that the effect of reservoirs on the dry season streamflow was not significant except 2013

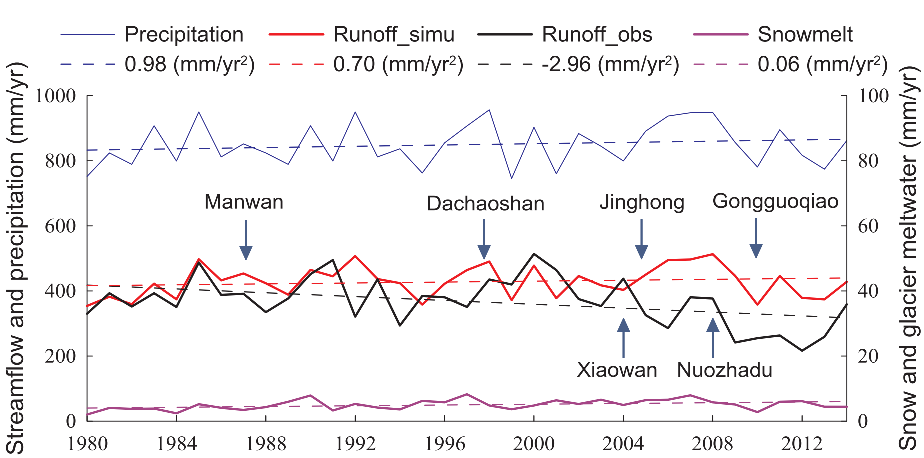

Fig. 3. Time series of annual mean precipitation, observed streamflow, simulated natural streamflow, and simulated snowmelt runoff in the LR basin during 1980–2014. Dashed lines represent trend lines of the four variables and the numbers in the legend represent their change rates. Arrows denote the initial construction time of the completed dams.

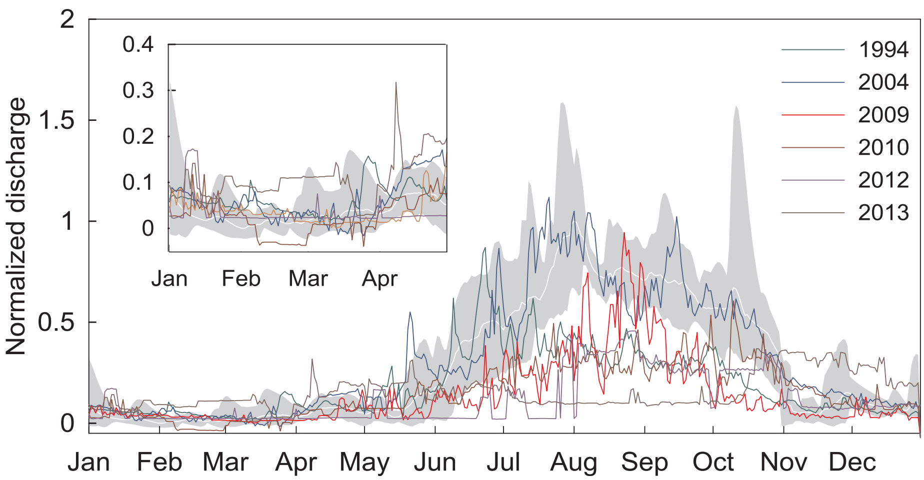

Fig. 5. Comparison between the normalized observed streamflow during 1980–1986 and normalized observed streamflow of specific years related to dam construction. Shading areas represent the range of the observed streamflow during the baseline period 1980–1986 and the white line represents the mean of the observed streamflow during the same period. The normalization is the same as that shown in Fig. 1. Maximum and minimum observed discharge at the Yunjinghong gauging station during the baseline period were used here.

when the dry season streamflow was almost highest among all years compared due to the completion of the Nuozhadu Reservoir. Räsänen et al. (2017) made a comparison of observed streamflow of 2010–2014 to observed streamflow of a baseline period (1960–1990) at Chiang Sean (in Thailand), Nakhon Phanom (in Vietnam) and Kratie (in Cambodia) gauging stations. In 2013 when all the reservoirs in the LR basin were completed, the wet season streamflow at Chiang Saen was lower than that during the baseline period, which applies to Yunjinghong in our study. However, streamflow in July, August, and September of 2013 at Nakhon Phanom and Kratie was even higher than that during the baseline period. We could therefore infer that reservoirs constructed in the LR basin has a certain impact on streamflow in Thailand, but has a less impact on streamflow in Vietnam and Cambodia.

4.3. Quantification of the impacts of climate change and human activities

Compared to the baseline period (1980–1986) when no dam was constructed, significant changes (~ −6%) in mean annual streamflow occurred from 1987 to 2014, particularly after 2008 when streamflow decreased by 26.8% compared with the baseline period. The contributions of climate change and human activities to changes in streamflow accounted for ~57% and ~43% for the transition time period (1987–2007), and ~5% and ~95% for the post-impact period (2008–2014), respectively (Table 3), compared with the baseline period (1980–1986).

During the transition time period, only two large reservoirs (Manwan and Dachaoshan) were built, with a total dead reservoir storage of 7.3 mm, whereas two other reservoirs (Jinghong and Xiaowan) were still under construction. The impact of human activities was therefore smaller than that of climate variation during this period, indicating that reservoir construction and operations did not significantly impact the flow regime of the LR basin during the transition period. During the post-impact period, all the six reservoirs were built, including the reservoir with the largest annual regulation (Nuozhadu) and the total dead storage capacity increased to 118.4 mm. The construction of large reservoirs has led to a rapid increase in the impact of human activities on streamflow.

Table 3 shows the contributions of climate change and human activities in each period after the reservoir was built. During 1987–1996, Manwan was the only reservoir on the LR, and then Dachaoshan was built and put into operation during 1997–2004. During 2005–2007, both Xiaowan and Jinghong were under construction and Nuozhadu and Gongguoqiao started to be built and put into operation during 2008–2012. All the reservoirs were completed during 2013–2014.

It was found that first, with increasing total dead storage of reservoirs on the LR, the impact of human activities on streamflow was increasingly important. Second, the impact of human activities was stronger when the time-lag between the activation period of two reservoirs was shorter. For example, the impact of human activities was 52.3% during 1997–2004 when there was only one reservoir under construction. It became 64.6% during 2005–2007 when two reservoirs were under construction and even raised to 90.5% during 2008–2012 when four reservoirs were built together. The impact of human activities on streamflow slightly reduced during 2013–2014, when all reservoirs were put into operation and there was no need to fill dead water storage of reservoirs.

In addition to the simulation performed by the hydrological model, the Budyko framework was also used to separate the effects of climate change and human activities at the annual scale. As shown in Table 4, the contributions of climate change and human activities to the changes in streamflow accounted for ~63% and ~37% for the transition time

Table 3
Human- and climate-induced changes on annual streamflow for each period after the reservoir was built. The three blod lines in the table represent the baseline period, transition period and post-impact period respectively.

Duration	Precipitation		Runoff observation		Runoff simulation		I_{cc}(%)	I_{ha}(%)
	(mm/yr)	Relative change (%)	(m^3/s)	Relative change (%)	(m^3/s)	Relative change (%)		
1980–1986	**833**	–	**1728**	–	**1867**	–	–	–
1987–1996	839	0.7	1736	0.5	1945	4.2	52.7	47.3
1997–2004	850	2.0	1881	8.9	1940	3.9	47.7	52.3
2005–2007	925	11.0	1485	−14.1	2163	17.1	35.4	64.6
1987–2007	**855**	**2.6**	**1755**	**1.6**	**1974**	**5.7**	**57.2**	**42.8**
2008–2012	860	3.2	1215	−29.7	1927	3.2	9.5	90.5
2013–2014	818	−1.8	1387	−19.7	1806	−3.3	17.5	82.5
							0.5	
2008–2014	**848**	**1.8**	**1264**	**−26.8**	**1893**	**1.4**	**5.0**	**95.0**

Table 4
Human- and climate-induced changes on annual streamflow calculated by the Budyko framework.

Time Period	P (mm/yr)	E_0 (mm/yr)	Q (mm/yr)	Budyko Framework	
				I_{cc} (%)	I_{ha} (%)
1980–1986	833	781	385	–	–
1987–2007	855	785	391	63.4	36.6
2008–2014	848	809	282	1.4	98.6

period 1987–2007, and ~1% and ~99% for the post-impact period 2008–2014, respectively. The difference between the two methods was approximately within 6%.

At the seasonal scale, during the transition period, human activities accounted for ~61% of wet season streamflow changes, whereas climatic variation accounted for ~60% of dry season streamflow changes. Similarly, during the post-impact period, human activities accounted for ~80% during the wet season, whereas climate change accounted for ~60% during the dry season. These findings indicate that human activities had a relatively larger contribution during the wet season whereas climate change was the dominant factor affecting the dry season streamflow. During the wet season, human activities contributed more in the post-impact period, providing benefits to the lower reaches with regard to flood control. For example, the flood control standard of the Jinghong Reservoir increased from 20 years to 100 years after the completion of the Nuozhadu Reservoir.

At the monthly scale, during the transition period, the streamflow was mostly influenced by climate change except July, August and October (Fig. 6). The contribution of climatic variation in March was greatest, accounting for ~67% of the streamflow changes. Snow and glacier meltwater in spring (March–May) increased by ~39% compared with the baseline period, and contributed to 4.5% of the spring streamflow. Therefore, the change in streamflow was mainly attributed to the change in precipitation. During the post-impact period, human activities contributed more to the changes in streamflow for most of months except February, May and November (Fig. 6). The contribution of human activities in June was greatest, accounting for ~97% of the streamflow changes. This is consistent with the trends illustrated above that human activities were the dominant factor affecting changes in streamflow, as the total reservoir dead storage capacity increased during the post-impact period and human activities mainly affected the streamflow during the wet season.

4.4. Separating effects of human activities

Not only reservoir construction and operation, but also other human interventions such as human water withdrawal changes and land cover changes might affect the flow regime of the LR. Fig. 7 shows annual mean water withdrawal time series including irrigation, livestock, manufacturing, domestic and mining and dead storage capacity of reservoirs in the LR basin. The proportion of irrigation, livestock, manufacturing, domestic and mining water use in total streamflow during the baseline period was 6%, 0.6%, 0.2%, 0.1% and 0.01%, respectively. It was found that irrigation, the largest component of water withdrawal in the LR basin, exhibited a decreasing trend, whereas manufacturing and domestic water withdrawal was almost doubled and water withdrawal for other purposes remained almost steady.

Under the impacts of human activities, streamflow reduced by ~50 mm in the LR basin during 1987–2010 compared with the baseline period. Water withdrawal was only increased by 0.8 mm compared with the baseline period that accounts for 1.6% of the streamflow change, while the dead reservoir storage increased by ~44 mm that accounts for 88% of the streamflow change. The land cover in the MRB changed by only 0.57% during 2000–2010, implying that the land use change was not a significant factor affecting the streamflow among human activities (Li et al., 2017a). Consequently, we can draw a conclusion that reservoir construction was the primary factor among human activities that impacted the flow regime during 1987–2010.

5. Discussion

This study evaluated annual, seasonal, and monthly changes in streamflow and attributed the changes to climate change and human activities in the LR basin over the time period 1980–2014, by applying the CREST-snow hydrological model and using long-term streamflow observations at the Yunjinghong gauging station. CREST-snow was calibrated for both streamflow and snow, allowing more reliable quantification of climate change impacts on streamflow. Runoff from the TP tends to be sensitive to climate change as a result of snow and glacier melting (Immerzeel et al., 2009; Jeelani et al., 2012). Finger et al. (2015) indicated that use of streamflow alone can lead to unrealistic glacier mass balances and snow cover evolution. The dual calibration with both streamflow and snow water equivalent performed in our study was therefore more appropriate to assess hydrological dynamics, though it would cause a certain loss in streamflow simulation performance.

Impacts of reservoir operations in the LR basin can be examined by

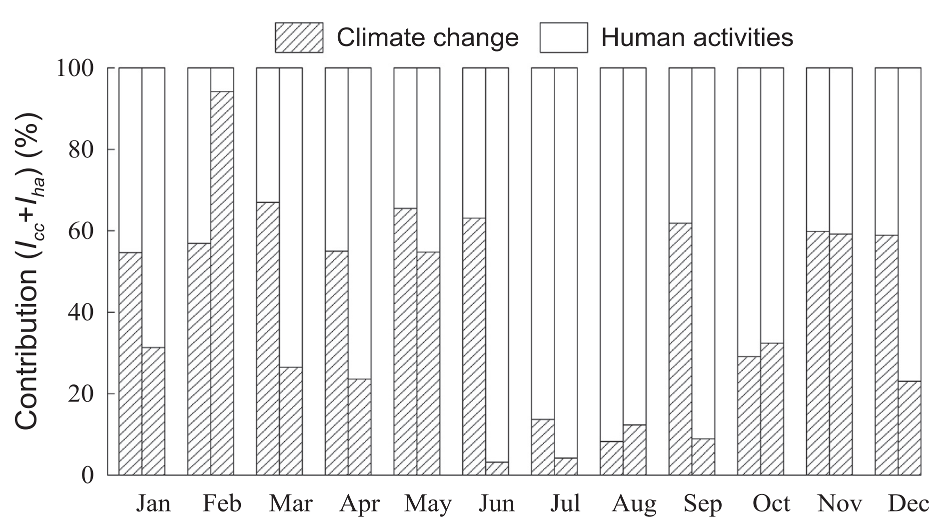

Fig. 6. Contributions of climate change and human activities to monthly streamflow changes. For each month, the column on the left represents the transition period whereas the column on the right represents the post-impact period.

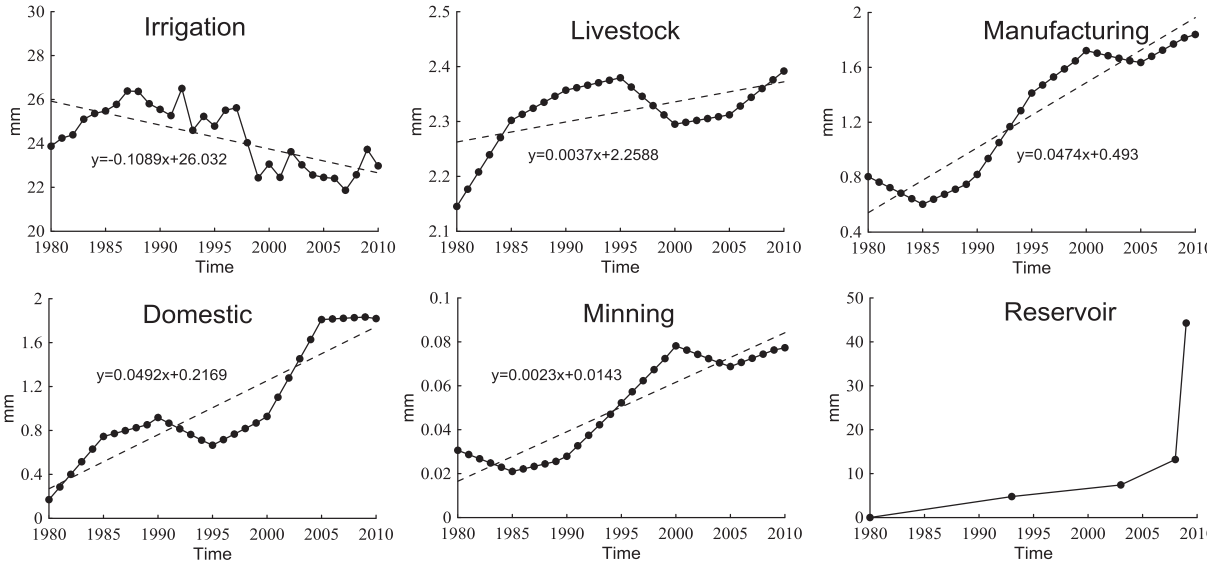

Fig. 7. Annual trends (dashed lines and linear regression equations) in mean water withdrawal and the dead storage of reservoirs in the LR basin.

looking at changes in streamflow between the baseline period (1980–1986) and the assessment period (1987–2014). In our study, we found that reservoirs stored water during the wet season with streamflow decreased by ~10% during the wet season of 1987–2014 compared with that of 1980–1986, and released water during the dry season with a ~10% increase in streamflow. Our findings were consistent with the recent assessment on hydrological alterations at the Chiang Saen gauging station (Li et al., 2017a; Räsänen et al., 2017; Wang et al., 2017). Such reservoir operations could bring great benefits to the downstream, with increasing dry season flows supplementing water resources for irrigation and reducing wet season flows mitigating flood risks downstream.

For example, influenced by the super El Nino during the dry season of 2016, all countries in the LR–MR basin suffered drought of varied degrees. The Chinese government implemented an emergency water supply to the MR by releasing water from the Jinghong Reservoir, which effectively alleviated the drought condition in the lower reaches (Li et al., 2017b). However, the building of large dams may cause geological damage, affect fish migration, and cost immense manpower, material and financial resources (Pokhrel et al., 2018). Evaluation of effects of dams on rivers requires an integrated consideration of various factors such as hydrology, ecology, and economy as well.

Regarding the attribution of changes in streamflow to climate change and human activities, we compared our estimates with two published studies. Tang et al. (2014) analyzed the contributions in the LR basin during 1956–2008, and found that climatic variation contributed more during the wet season whereas human activities contributed more during the dry season, in contrary to our findings. Note that their study calibrated and validated streamflow at the monthly scale, as opposed to the daily scale performed in our study. The BP-ANN model they used to simulate the natural streamflow may not well reflect the underlying mechanisms and hydrological processes. Different time periods of these analyses may also be one of the reasons for the different findings. In addition, Li et al. (2017a) used the Budyko hypothesis to partition the effects of climate change and human activities on the streamflow changes and concluded that climate change contributed to ~82% of the total streamflow change during the transition period 1992–2009, whereas human activities contributed to ~62% of the total change during the post-impact period 2010–2015 in the upper MRB with the basin outlet located at Chiang Saen, which was highly consistent with our results.

Furthermore, the contribution of human activities was found to have decreased from 95% at Yunjinghong to 62% at Chiang Saen. The Chiang Saen gauging station in Thailand is on the south of the Yunjinghong gauging station with a warmer climate and much more precipitation. Some research showed that not only precipitation but also interval inflow between the Yunjinghong and Chiang Saen gauging stations were important components of streamflow at the Chiang Saen station (He et al., 2006). It was therefore implied that precipitation is the main source of freshwater resources for the lower MRB, and the impact of dam operations on the LR would become less important downstream. Still, different study periods and analysis approaches may have induced some discrepancies in the results.

There are also limitations in this study. The precipitation data that we used has some uncertainties. Precipitation is the primary forcing in hydrological models. The LR originating on the TP at over 5100 m elevations has sparse in situ observations, so the quality of the CGDPA precipitation product used in this study may be degraded relative to regions with denser observational networks in eastern and central China. Although some studies (Pan et al., 2010; Wang et al., 2017) demonstrated that remote sensing precipitation products can be used to effectively simulate hydrological processes in basins including the MRB, the currently available remote sensing products could not cover such a long time period from 1980 to 2014. More accurate precipitation products at higher spatial resolutions are expected to improve the model performance in the future. Also, CREST-snow showed some degraded reproduction of the observed streamflow during the baseline period 1980–1986 (Fig. 2). These inaccuracies might be associated with uncertainties in precipitation, and calibration of the model parameters, leading to uncertainties in differentiating the climate- and human-induced streamflow changes.

This study was conducted over the time period 1980–2014 when there were only six large reservoirs built on the mainstream of the LR. The total dead reservoir storage of the six existing reservoirs represents ~40% of the annual streamflow at the Yunjinghong gauging station. The magnitude of streamflow at Yungjinghong would recover to a state prior to dam construction in the future if there is no filling of dead reservoir storage and water use does not largely increase. There is a further need for estimating future impacts of climate change and hydropower development in the LR basin to provide a basis for water resources management, especially for transboundary river management.

6. Conclusion

This study aims to estimate streamflow changes caused by climate

change and human activities in the LR basin over a historical 35-year period (1980–2014) using the CREST-snow hydrological model and streamflow observations at the Yunjinghong gauging station. CREST-snow was calibrated with streamflow and snow water equivalent data. Based on the history of dam construction and the intercept break point determined by the Mann-Kendall test, the 35-year period was partitioned into three time windows for our analysis, and the contributions of climate change and human activities were investigated at annual, seasonal and monthly scales. The major findings of this study are summarized as follows.

(1) A significant change ($\sim -6\%$) in mean annual streamflow occurred during 1987–2014 compared with that of the baseline period, especially after year 2008 when the largest hydropower plant (Nuozhadu) in the MRB began to build. Increased streamflow during the dry season and decreased streamflow during the wet season were found.
(2) Compared with the baseline period 1980–1986, climatic change and human activities contributed $\sim 57\%$ and $\sim 43\%$ to the streamflow changes for the transition time period 1987–2007, and $\sim 5\%$ and $\sim 95\%$ for the post-impact period 2008–2014, respectively. Reservoir construction was the most significant factor affecting streamflow among human activities including agricultural, industrial, and domestic water uses.
(3) At the seasonal scale, climatic variation contributed more during the dry season, and precipitation change was the dominant factor that resulted in streamflow changes. Human activities were the dominant factor leading to streamflow changes during the wet season mainly through reservoir filling. Streamflow released from the reservoirs during the dry season could benefit irrigation and the reduced wet season discharge could mitigate food risks downstream.

Overall, this study can serve as a basis for understanding hydrological changes in dammed rivers, and provide reference for water resources management for the transboundary LR-MR basin. Projections of future runoff under climate change scenarios should consider reservoir construction and operation strategies, and more research is needed to understand implications of the streamflow changes in the dammed river on hydropower generation, ecosystems, and society.

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